DOOR: towards a formalization of ontology relations

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DOOR:
Towards a Formalization of Ontology Relations

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Abstract: In this paper, we describe our ongoing effort in describing and formalizing semantic relations that link ontologies with each others on the Semantic Web in order to create an ontology, DOOR, to represent, manipulate and reason upon these relations. DOOR is a Descriptive Ontology of Ontology Relations which intends to define relations such as inclusion, versioning, similarity and agreement using ontological primitives as well as rules. Here, we provide a detailed description of the methodology used to design the DOOR ontology, as well as an overview of its content. We also describe how DOOR is used in a complete framework (called KANNEL) for detecting and managing semantic relations between ontologies in large ontology repositories. Applied in the context of a large collection of automatically crawled ontologies, DOOR and KANNEL provide a starting point for analyzing the underlying structure of the network of ontologies that is the Semantic Web.

1 INTRODUCTION

Ontologies are the pillars of the Semantic Web (SW) and, as more and more ontologies are made available online, the SW is quickly taking shape. As a result, the research community is becoming more and more aware that ontologies are not isolated artifacts: they are, explicitly or implicitly, related with each other (Kleshchev and Artemjeva, 2005). Indeed, a number of studies have intended to tackle some of the challenges raised by these ontology relationships, from both theoretical and practical points of view.

At a theoretical level, studies have targeted ontology comparison in order to identify overlaps between ontologies (Maedche and Staab, 2002). Approaches have been proposed to find differences between versions of an ontologies (Noy and Musen, 2002; Konev et al., 2008). According to (Klein and Fensel, 2001), the ontology versioning problem has been defined as *the ability to handle changes in ontologies by creating and managing different variants of it.* In other words, ontology versioning means that there are multiple variants of an ontology around. The authors of (Klein and Fensel, 2001) suggested that, ideally, developers should maintain not only the different versions of an ontology, but also some information about the way versions differ and whether or not they are compatible with each other. In (Gangemi et al., 1999) ontology integration is defined as the construction of an ontology C that formally specifies the union of the vocabularies of two other ontologies A and B. The most interesting case is when A and B are supposed to commit to the conceptualization of the same domain of interest or of two overlapping domains. In particular, A and B may be related by being *alternative ontologies*, *truly overlapping ontologies*, *equivalent ontologies with vocabulary mismatches*, *overlapping ontologies with disjoint domain*, *homonymically overlapping ontologies*. Finally, in ontology matching, an alignment is set of correspondences between the entities of two ontologies, therefore relating these two ontologies by mapping there models with each other.

At a practical level, Semantic Web Applications use the SW as a large-scale knowledge source (d'Aquin et al., 2008): they achieve their tasks by automatically retrieving and exploiting knowledge from the SW as a whole, using advanced Semantic Web Search Engines (SWSEs) such as WATSON (d'Aquin et al., 2007). These SWSEs provide keyword based search mechanisms to locate relevant ontologies for particular applications. As an example, the query "*student*" currently gives 1079 ontologies as a result in WATSON[1] (valid on the 22/04/2009). However, these results are provided as a simple list without making explicit the underlying relations that link ontologies with each other. Indeed, on the first page, at least 2 of the ontologies (`http://www.vistology.com/ont/tests/student1.owl` and `http://www.vistology.com/ont/tests/student2.owl`) represent, apart from their URIs and the base namespaces, exactly the same logical model, expressed in the same ontology language. Another common situation is when an ontology has been translated in different ontology languages. This is the case in the first and second results of the query "*student, university, researcher*"(`http://reliant.teknowledge.com/DAML/Mid-level-ontology.owl` and `http://reliant.teknowledge.com/DAML/Mid-level-ontology.daml`). These two ontologies are obviously two different encodings of the same model. Inspecting the results of WATSON in the same way, it is not hard to find ontologies connected with other, more sophisticated semantic relations: *versioning*, *inclusion*, *similarity*, etc. Leaving implicit these relations in SWSE's ontology repositories generates additional difficulties in exploiting their results, expecting the users and the applications to find the "right" or "best" ontology to achieve their goal.

Both the theoretical and practical challenges concerning relations between ontologies indicate a need for a general study of these relations, providing a formal base for defining, manipulating and reasoning upon the links that relate ontologies online, explicitly or implicitly. Here, we chose to take an ontological approach to this problem. We design DOOR, a Descriptive Ontology of Ontology Relations that defines ontology relations using ontological primitives and rules. Apart from the ontology itself, the main contributions of this work concern the realization of a methodology to identify and define relations between ontologies, as well as the development of a complete system based on DOOR (KANNEL), providing services for detecting relations, populating DOOR, and formally querying detected and inferred relations in a large ontology repository.

This paper is structured as follows: in Section 2 we continue discussing significant work concerning ontology relations; Section 3 presents the adopted methodology for designing DOOR; Section 4 describes the DOOR ontology; In Section 5 we briefly describe KANNEL and the main role of DOOR in this framework. Finally, Section 6 concludes the paper and sheds the light on interesting future research on ontology relations.

[1]`http://watson.kmi.open.ac.uk`

2 RELATED WORK

J. Heflin (Heflin and Pan., 2004) was the first to studied formally some of the different types of links between ontologies, focusing on the crucial problems of versioning and evolution. However, currently, there is no Ontology Management Systems that implements his framework. The authors of (Kleshchev and Artemjeva, 2005) characterized, at a very abstract level, a number of relations between ontologies such as *sameConceptualization*, *Resemblance*, *Simplification* and *Composition*, without providing formal definitions for them, and without considering the links between these relationships. Several approaches have been focusing on how to compare two different versions of ontologies in order to find the differences. In particular, PROMTDIF (Noy and Musen, 2002) compares the structure of ontologies and OWLDiff (`http://semanticweb.org/wiki/OWLDiff`) computes the differences by entailment, checking the two set of axioms. SemVersion (Volkel, 2006) compares two ontologies and computes the differences at both the structural and the semantic levels. In addition, many measures exist to compute particular forms of similarity between ontologies (David and Euzenat, 2008).

All these studies discuss particular relations separately and are generally based on an abstract, informal definition of the relations they consider. A complete model is necessary to provide a wide overview of existing ontology relations, to clearly establish what are their definitions, formal properties, and how they are connected with each other.

3 METHODOLOGY FOR THE DOOR ONTOLOGY

Building an ontology of relationships between ontologies is a very ambitious task. It requires a deep analysis of the ontologies available online and of the literature, at different levels. Therefore, a reasonably rigorous but nonetheless flexible methodology is needed to identify, describe and formalize ontology relations and their connections, in order to build the DOOR ontology. Here, after defining some important elements that will be used in the rest of the paper, we present the steps involved in the methodology we adopted and briefly detail each of them.

3.1 Definitions and Requirements

We consider the following definitions:

Definition 1 (Ontology) *An ontology is a set of axioms (in the sense of the description logic) over a Vocabulary VOC, where VOC is the set of the primitive terms (named entities) employed in the axioms of the ontology;*

Definition 2 (Ontology Space) *An ontology space OS, is a collection of ontologies.*

Definition 3 (Ontology Relation) *Given an ontology space OS, an Ontology Relation is any binary relation defined over OS.*

At the most general level, the design of the DOOR ontology was based on three main sources to identify relevant ontology relations:

1. We analyzed the results of SWSEs (e.g., WATSON) to manually identify existing, implicit relations between ontologies in these results.
2. We considered relations described in the literature, such as the ones already mentioned in the previous sections.
3. We also included existing, explicit relations that are primitives of the OWL ontology language.

Also, ontology relations in the DOOR ontology should reflect the following important features:

- they are general enough to be applied to multiple domains;
- they are sufficiently intuitive to reflect general meaning;
- they are formally defined to be processed automatically by inference engines;

3.2 Main steps of the Methodology

To design DOOR, we considered the methodology described in (Gangemi et al., 2001) for selecting general ontological categories and adapted it to the problem of ontology relations. As a result, we divided our approach into a number of steps, as follows:

1. Identifying the top level relations between ontologies, considering our three sources (SWSEs, literature and existing OWL primitives). At this stage, the task only consists in coming up with a list of relations that should be relevant, giving us a general overview of the different sections of the ontology. Relations such as *inclusion*, *similarity*, *incompatibility* and *previous version* are identified here.
2. Specifying the identified relations, identifying relevant variants and sub-relations. Here, our three sources of relations are also employed to derive relations at a lower level than the top ones. We also use a more systematic approach, which consists in looking at ontologies (and so ontology relations) from 5 different dimensions that can characterize them:
   - **The Lexicographic level**, which concerns the comparison of the vocabularies of the ontologies.
   - **Syntactic level**, which concerns the comparison of the sets of axioms that form the ontologies.
   - **Structural level**, which concerns the comparison of the graph structure formed by the axioms of the ontologies.
   - **Semantic level**, which concerns the comparison of the formal models of the ontologies, looking in particular at their logical consequences.
   - **Temporal level**, which concerns the analysis of the evolution of ontologies in time.

   For example, considering the relation of *inclusion* identified in the first step and that led to a property *includedIn* in the ontology, we can specify this relation according to three different dimensions (syntactic, structural and semantic), leading to three variants of inclusion between ontologies (*syntacticallyIncludedIn*, *isHomomorphicTo* and *semanticallyIncludedIn*) that consider the set of axioms, the graph and the formal models of the ontologies respectivly. In addition, besides the systematic analysis of this relation according to the dimensions, we include in DOOR particular forms of inclusions derived from existing OWL primitives (e.g., OWL *imports*) and from the literature (e.g, *isAConservativeExtensionOf* (Ghilardi et al., 2006)). More details about these relations are given in the next section.
3. Characterizing each relation by its algebraic properties. For example, the algebraic properties for similarity are that it is *reflexive* and *symmetric*. For inclusion, we can define that it is *reflexive* and *transitive*. Including such information in the ontology corresponds to what (Gangemi et al., 2001) calls defining the *ground axioms*.
4. Establishing connections between relations. The results obtained from the previous steps are mainly top-level relations with a list of variants, each of them being given algebraic properties.

Here, we want to structure these lists, in particular by giving them taxonomic relations. As an example, it can be easily established that *syntacticallySimilarTo* is a sub property of *semanticallySimilarTo*. In the same way, we can indicate that a *previous version* of an ontology ought to be *similar* to it. This corresponds to defining *non-ground axioms* in (Gangemi et al., 2001).

5. Introducing rules to define complex relations from atomic ones. For example, the *equivalentTo* property can be defined as *equivalentTo*(X_1, X_2)*:- includedIn*(X_1, X_2)*, includedIn*(X_2, X_1)*.*

Like in any methodology, the application of these steps should be flexible and continuous. Getting back to a previous step is sometimes necessary and, as the building of an ontology such as DOOR is a constantly ongoing effort, it should be possible to re-apply the methodology entirely to make the ontology evolve.

The intended result is an ontology made, on the one hand, of an ontologically defined and taxonomically structured set of relations, and on the other hand, of a set of rules to define complex relations. In the following we give a detailed overview of the first version of the DOOR ontology, considering only the first (ontological) part of it, as, due to its complexity, the definition of rules governing complex relations is still a work in progress and would not fit in this paper.

4 FORMAL DESCRIPTION OF DOOR

The OWL version of the DOOR ontology can be downloaded at: `http://kannel.open.ac.uk/ontology`.We start with describing the first level of DOOR, in Figure 2. The main relevant abstract relations are simply represented as sub-properties of *ontologyRelatedTo*. An ontology X is *ontologyRelatedTo* another one Y if one of the top level relations is satisfied between X and Y. The top level relations include *includedIn*, *similarTo*, *isAlignedTo*, *disagreesWith*, *agreesWith* and *isTheSchemaFor*. We clustered them in four groups and each group will be explained in more details in the next sub-sections.

4.1 includedIn and equivalentTo

includedIn and *equivalentTo* are two of the main ontology relations. The former represents the meaning of “an ontology contains an another one”. The latter intends to convey the meaning of “two ontologies express the same knowledge”. According to our methodology, these two relations have been analyzed at different levels, giving origin to different kinds of

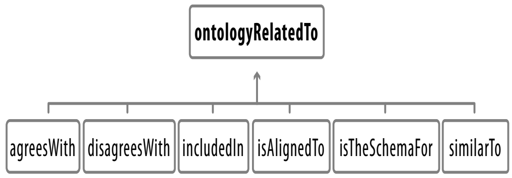

Figure 1: **Top Level of DOOR.**

inclusion and *equivalence* relations. In Table 1, we summarize the result of these analyses:

Table 1: Specialization of inclusion and equivalence relations.

	includedIn	equivalentTo
Semantic	semanticallyIncludedIn isAConservativeExtentionOf	semanticallyEquivalentTo
Structural	isHomomorphicTo	isIsomorphicTo
Syntactic	syntacticallyIncludedIn import	syntacticallyEquivalentTo

In particular, the sub-relations of *includedIn* are defined as follows:

SyntacticallyIncludedIn(X_1**,** X_2) if the set of axioms of X_1 is contained in the set of axioms of X_2,which means $X_1 \subseteq X_2$.

isHomomorphicTo(X_1**,** X_2) if a homomorphism exists between the RDF-graph of X_1 and the RDF-graph of the X_2.

SemanticallyIncludedIn(X_1**,** X_2) if the set of models of X_1 is contained in the set of models of X_2. In other words, if $X_1 \models X_2$.

isAConservativeExtentionOf(X_1**,** X_2) , informally, if *syntacticallyIncludedIn*(X_2, X_1) and all the axioms entailed by X_1 over the vocabulary of X_2 are also entailed by X_2. A more formal definition can be found in (Ghilardi et al., 2006). The notion of conservative extension has been used in particular for ontology modularization (Grau et al., 2007).

import(X_1**,** X_2) if there is an explicit statement in X_1 indicating that it imports X_2 using the *owl:imports* primitive. Formally, this means that all the axioms of X_2 should be considered as contained in X_1.

The sub-relations of *equivalentTo* are defined as follows:

syntacticallyEquivalentTo(X_1**,** X_2) if and only if *SyntacticallyIncludedIn*(X_1, X_2) and *SyntacticallyIncludedIn*(X_2, X_1).

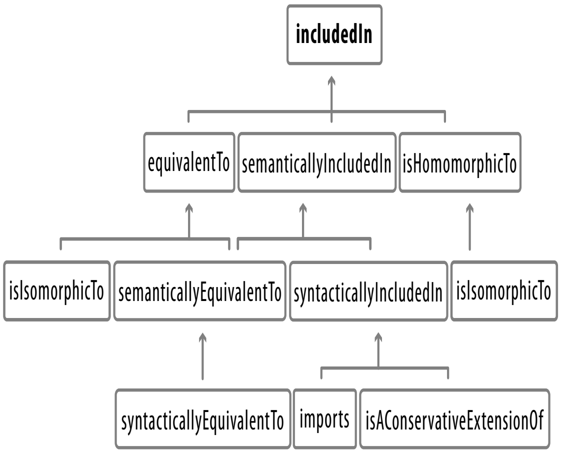

Figure 2: **Taxonomy for includedIn and equivalentTo**

isIsomorphicTo(*X_1*,* X_2*) if an isomorphism exists between the graph of X_1 and the graph of X_2.

SemanticallyEquivalentTo if and only if *SemanticallyIncludedIn(*X_1*,* X_2*)* and *SemanticallyIncludedIn(*X_2*,* X_1*)*.

Finally, following our methodology, we defined the algebraic properties of each relation[2] and classified them to create a taxonomic structure relating these relations. This structure is showed in Figure 2[3].

4.2 similarTo

Ontology similarity has been described as a measure to assess how close two ontologies are (David and Euzenat, 2008). Various ways to compute the similarity between two ontologies have been described which are relevant in different application contexts. In our work, *similarTo* is used to represent the meaning of "how an ontology overlap/cover parts of the same area of interest of another ontology". Following our methodology, *similarTo* has been analyzed and formalized at the lexicographic, structural and semantic level, giving origin to different kinds of similarity relations (see Table 2).

To define these relations, we need to introduce the following elements: given two ontologies X_1 and X_2, we denote by *LC(*X_1*,* X_2*)* the set of axioms of X_1 that are logical consequences of X_2 and by *Voc(*X_1*)* the vocabulary of X_1. The following definitions depend on a threshold $T > 0$.

[2]Since these are fairly obvious, we do not detail then.

[3]The arrows represent the subPropertyOf relation. For example, syntacticallyEquivalentTo is a sub property of semanticallyIncludedIn.

Table 2: Specialization of the similarity relation

	SimilarTo
Semantic	SemanticallySimilarTo
	MappingSimilarTo
Syntactic	SyntatticallySimilarTo
Lexicographic	LexicographicSimilarTo

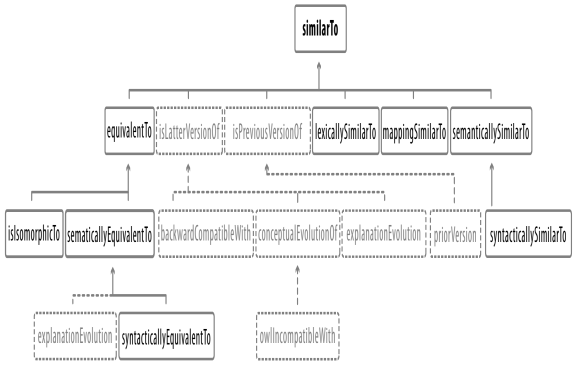

Figure 3: **Taxonomy for similarTo. Dashed elements represent elements from other sections of the ontology.**

semanticallySimilarTo(*X_1*,* X_2*), if

$$\frac{|LC(X_1,X_2)\bigcap LC(X_2,X_1)|}{max(|X_1|,|X_2|)} \geq T$$

syntacticallySimilarTo(*X_1*,* X_2*), if

$$\frac{|X_1 \bigcap X_2|}{max(|X_1|,|X_2|)} \geq T$$

lexicographicallySimilarTo(*X_1*,* X_2*), if

$$\frac{|Voc(X_1)\bigcap Voc(X_2)|}{max(|Voc(X_1)|,|Voc(X_2)|)} \geq T$$

Finally, in addition to the relations defined above, we also consider a similarity relation that relies on the existence of an alignment between the two ontologies. Indeed, **mappingSimilarTo** is a relation that links two ontologies X_1 and X_2 if there exists an alignment from X_1 to X_2 and this alignment covers a substantial part of the vocabulary of X_1 (i.e., a proportion greater than a threshold T). Not that, since alignments can be unidirectional, *mappingSimilarTo* differs from the other similarity functions by not being symmetric.

Finally, we have classified the relations in Table 1 to create the taxonomic structure showed in Figure 3.

4.3 Versioning

Versioning is a temporal relation that concerns the evolution of an ontology. In (Klein and Fensel, 2001), the ontology versioning problem has been defined as *the ability to handle changes in ontologies by creating and managing different variants of it.*

An ontology can evolve over time in different directions, e.g. *lexicographic*, changing the names of some resources, *syntactic*, adding or removing axioms, *semantic*, changing the definition of some concepts or simply adding or removing axioms. Therefore, the new ontology could be equivalent or totally different from the previous one. When we analyze different ways of linking two ontologies by the versioning relation, the two following sentences are suggested immediately: “X_1 is the previous version of the X_2” or “X_2 is the latter version of the X_1”. These two typical pieces of knowledge are represented in the DOOR ontology by the relations *isPreviousVersionOf* and its inverse *isLatterVersionOf* respectively.

Conforming to our methodology, the *isPreviousVersionOf* and *isLatterVersionOf* relations have been analyzed and formalized, to identify sub-relations and variants. In Table 3 we summarize the result of this analysis.

Table 3: Specialization of the versioning relations.

	isLatterVersionOf	isPreviousVersionOf
Temporal	conceptualEvolutionOf explanationEvolutionOf backwardCompatibleWith owl:IncompatibleWith	priorVersion
Semantic	conceptualEvolutionOf	
Syntactic	explanationEvolutionOf	

According to (Klein et al., 2002; Heflin and Pan., 2004; Heflin, 2001) the modification of an ontology can lead to two different types of evolutions: being a conceptual change, meaning that the model of the ontology changed, or being an explanation change, meaning that the modifications happened only at a syntactic level, without affecting the model of the ontology. Therefore, we specialized the *isLatterVersionOf* relation into

conceptualEvolutionOf(X_1,X_2) if X_1 is a latter version that is not semantically equivalent to X_2.

explanationEvolutionOf(X_1,X_2) if X_1 is a latter version that is semantically equivalent to X_2

These two relations will lead to the definition of rules to infer them from equivalence and other versioning relations.

In addition, the OWL ontology properties *priorVersion*, *backwardCompatibleWith* and *incompatibleWith* represent explicit relations between versions of ontologies and are included in

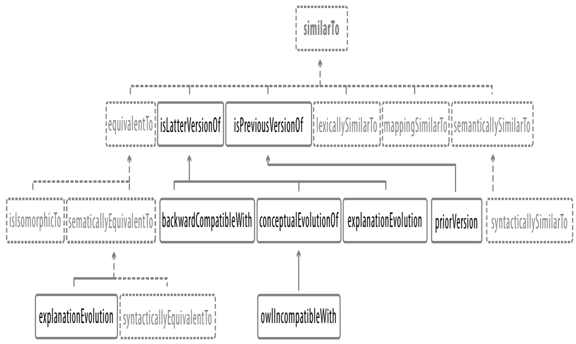

Figure 4: **Taxonomy for versioning relations.**

DOOR as sub-properties of *isLatterVersionOf* and *isPreviousVersionOf*.

To complete this section of the DOOR ontology, we can classified the relations in Table 3 as showed in Figure 4.

Indeed, according to (Klein et al., 2002; Heflin and Pan., 2004; Heflin, 2001) the modification of an ontology can lead a new version which is completely different from the original one. But in practice, by analyzing Watson’s ontology repository, it is almost always possible establish a similarity between the two ontologies, at least at the lexicographic level. Due to this fact, we chose to consider the versioning relations to be sub-properties of *similarTo*, to indicate that two different versions of the same ontology should, to some extent, be similar. Moreover, in accordance with its definition, the *explanationEvolutionOf* relation is a sub-property of *semanticallyEquivalentTo*.

4.4 Agree and Disagree

Based on the formal measure of the agreement and disagreement between two ontologies presented in (d’Aquin, 2009), we introduce the *agreesWith* and *disagreesWith* relations in DOOR. Informally, the former holds the general meaning of “to have the same opinion about something”. In other words, it connects two ontologies, sharing the same knowledge partially and is therefore very related to the *similarTo* and the *equivalentTo* relations. The later indicates that the ontologies “contradict each other” to a certain extent, these contradictions appearing at various levels. Envisaged sub-relations for these two relations are listed in Table 4.

In this Table, all the sub-relations of *agreesWith* have already been defined before. We add a few relations to express specific ways for ontologies to disagree, all related to the semantic dimension of the on-

Table 4: Specialization of agreesWith and disagreesWith.

	agreeWith	disagreeWith
Temporal	backwardCompatibleWith	owlIcompatibleWith
Semantic	sematicallyEquivalentTo sematicallySimilarTo	hasDisparateModeling incompatibleWith incoherentWith incosistentWith
Syntactic	syntacticallyEquivalentTo syntacticallySimilarTo explanationEvolution	

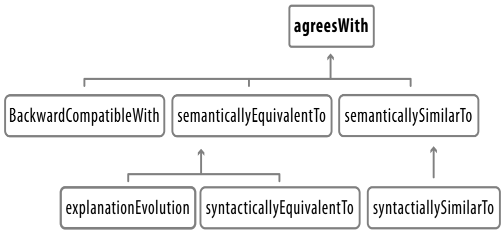

Figure 5: **Taxonomy for the agreement relations.**

tologies.

incompatibleWith(X_1, X_2) if *incoherentWith(X_1, X_2)* or *inconsistentWith(X_1, X_2)*.

incoherentWith According to (Qi and Hunter, 2007) an ontology X_1 is incoherent if and only if there is an unsatisfiable concept name in X_1. Therefore, two ontologies are *incoherent* with each other if, when they are merged, they generate an incoherent result.

inconsistentWith According to (Bell et al., 2007) an ontology X_1 is inconsistent if it has no model. Therefore, two ontologies are *inconsistent* with each other if, when they are merged, they generate a inconsistent result.

hasDisparateModeling besides the logical notion of disagreement, we also consider disagreements related to the conceptualization of the ontologies. Two ontologies are considered to have disparate modeling if they represent corresponding entities in different ways, e.g. as an instance in one case and a class in the other.

owl:CompatibleWith It comes from OWL language (Patel-Schneider et al., 2004).

Finally, we have also classified the relations in Table 4 as showed in Figures 5 and 6.

4.5 isTheSchemaFor and isAlignedTo

Analyzing Watson's ontology repository we found out that there are many documents which only represent

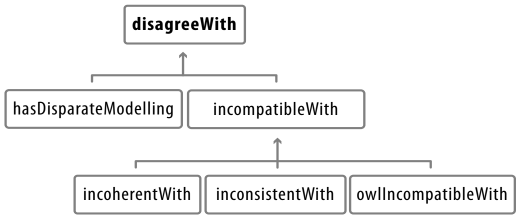

Figure 6: **Taxonomy for the disagreement relations.**

the TBox of an ontology and others representing just the ABox. By the *isTheSchemaFor* relation we want to keep the link between the TBox and the corresponding ABox, which is very important when we want to retrieve information.*isAlignedTo* relation is not well defined yet.

5 KANNEL: AN APPLICATION FOR THE DOOR ONTOLOGY

In the previous section, we described the DOOR ontology in detail. Here we provide a brief overview of the way it is used in the KANNEL system. KANNEL (Allocca., 2009) is a framework for detecting and managing ontology relations for large ontology repositories, such as WATSON. It is an ontology-based system where the DOOR ontology plays an important role, providing an explicit representation of the implicit relations between ontologies. We have designed an architecture for this framework, as depicted in Figure 7. As showed in this figure, the DOOR Ontology separates the on-line part of the architecture–providing APIs and services that relies on a reasoner–from the off-line part–detecting relations in the repository and populating the ontology. The offline part is based on three components: the *Control Component (CC)*, the *Detecting Component (DC)* and the *Populating Component (PC)*. As a first step, the CC selects from the Ontology Repository ontologies that need to be evaluated to establish potential relations. Then, the selected sets of ontologies are processed by the DC, which contains the main mechanisms to discover the possible relations between ontologies, relying on the definitions provided in this paper. Finally, the PC populates the semantic structure with the detected relations. What is obtained is a set of automatically discovered relations, represented as part of the DOOR ontology so that the reasoner used in the system can infer new relations from the ontological and rule based knowledge included in the ontology. As such, DOOR provides meta-information on the ontology repository in KANNEL.

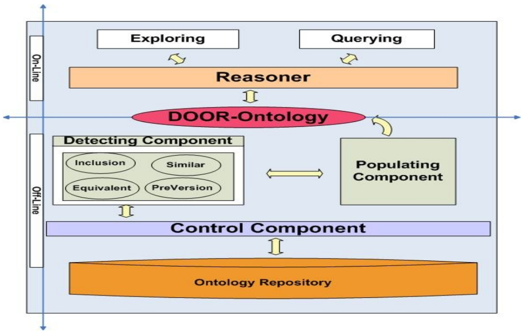

Figure 7: **Architecture of the KANNEL framework.**

6 CONCLUSIONS

In this paper, general relationships between ontologies have been examined. In particular, we have chosen to consider well-known relations in the literature, as well as the ones needed to support the development of Semantic Web Applications. To achieve that, we adapted an ontology building methodology for the construction of DOOR, an ontology of relations between ontologies. This ontology describes relations both from the point of view of their taxonomic structure and from the point of view of their formal definitions, providing the formal properties to describe them as well as a set of rules to derive complex relations from other relations.

We also described KANNEL, a framework for detecting and managing ontology relationships for large ontology repositories. The DOOR ontology plays a fundamental role in KANNEL, not only to provide an explicit representation on ontology relations, but also to supply meta-information that offers several advantages, among which the possibility to reason upon ontologies and their relations. This possibility provides a relevant support for the development of Semantic Web Applications, which can use the semantic web as a large-scale knowledge source (d'Aquin et al., 2008).

The first version of the DOOR ontology is available in OWL at `http://kannel.open.ac.uk/ontology`. The KANNEL framework is currently under development. The development of DOOR is obviously a continuous task, which requires a proper assessment of each version. For this reason, we plan to test and validate the first version presented here, in particular by populating it with automatically detected relations between ontologies in WATSON.

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